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Influence of Higher Order Modes on Angled-Facet Amplifiers

Z. Wang, B. Mikkelsen, and K. E. Stubkjaer

***Abstract*—The influence of the first-order mode on the residual reflectivity of angled-facet amplifiers is analyzed. For a 7° angled-facet ridge waveguide amplifier with a single-layer AR coating, a gain ripple lower than 1 dB at 25 dB gain can be obtained independent of the polarization, even in the presence of a first-order mode with a 15 dB gain. But the tolerances for the thickness and refractive index of the AR coating are reduced by a factor of three compared to operation in the fundamental mode only. The influence of the higher order mode can virtually be suppressed by increasing the facet angles to 10°.**

Introduction

ANGLED-FACET amplifiers are of increasing interest due to their inherently low modal reflectivity, and good performance has been obtained for angled-facet amplifiers with both 7° and 10° facet angles [1]–[3]. It is well known that for a given facet angle, a wider active region results in a lower modal reflectivity; however, this wide active region can also lead to the presence of the first-order mode [2]. The influence of the higher order modes on the gain ripple of straight facet amplifiers was discussed in [4]. Here we will analyze the influence of the first-order mode on the gain ripple of angled-facet amplifiers as a function of the facet angle.

Analysis

Two-dimensional models are sufficient for calculating the mode coupling of a straight-facet amplifier due to the relatively large beamwidth in the junction plane [5]. In the case of angled-facet amplifiers, the waveguide is tilted in the junction plane and a three-dimensional model is necessary. Here we have used a previously developed three-dimensional model [6] to investigate the modal coupling at the facets of the amplifier. The model accounts for both the amplitude and phase changes of the light reflected from the angled facet. The fields of the fundamental and the first-order modes are assumed to follow Hermite–Gaussian functions. This has proved to be an acceptable approximation by comparing the calculated and the measured far fields of the angled devices [7]. With a reference plane coincident with the facets (see Fig. 1), the plane wave spectra of the fields of the fundamental mode $F_0(\alpha, \beta)$ and the first-order mode $F_1(\alpha, \beta)$ are given by

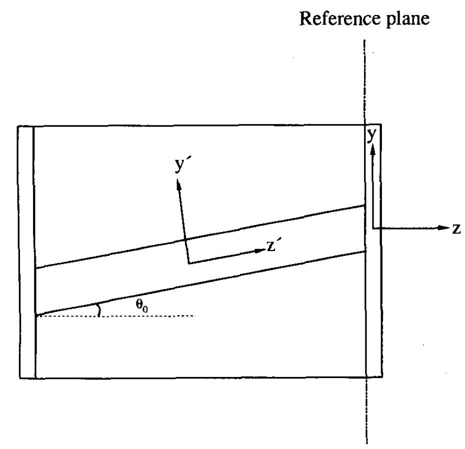

Fig. 1. Schematic of an angled-facet amplifier.

$$F_0(\alpha, \beta) = \frac{\sqrt{\pi}\, W_x W_y}{\lambda^2 \cos\theta_0} \cdot \exp\left(\frac{-\pi^2 n_1^2\left(W_y^2(\gamma\sin\theta_0 + \beta\cos\theta_0)^2 + \alpha^2 W_x^2\right)}{\lambda^2}\right) \tag{1}$$

$$F_1(\alpha, \beta) = \frac{\sqrt{2}\,\pi n_1 W_y}{\lambda}(\gamma\sin\theta_0 + \beta\cos\theta_0) F_0(\alpha, \beta)\exp\left(j\frac{\pi}{2}\right) \tag{2}$$

W_x and W_y are the 1/e-widths of the field inside the cavity; λ is the wavelength; α, β, and γ are the directional cosines in the coordinate system xyz; and θ_0 is the angle of the waveguide to the facet normal. The effective refractive index n_1 is approximately the same for both the fundamental mode and the first-order mode. The modal coupling taking place at the facet from the incident mode l to the mode m is given by

$$K_{lm} = \frac{1}{C_l C_m} \cdot \left| \int\int_{-\infty}^{+\infty} F_l(\alpha, \beta) Q(\alpha, \beta) F_m(\alpha, \beta)\, d\alpha\, d\beta \right|^2 \qquad l, m = 0, 1 \tag{3}$$

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$$C_l = \int \int_{-\infty}^{+\infty} q(\alpha, \beta) \,|\, F_l(\alpha, \beta) \,|^2 \, d\alpha \, d\beta \qquad l = 0, 1 \tag{4}$$

where $q(\alpha, \beta)$ is given by $(1 - \beta^2)/\gamma$ for the TE mode, and $(1 - \alpha^2)/\gamma$ for the TM mode. The coupling factor $Q(\alpha, \beta)$ is given by [8]

$$Q(\alpha, \beta) = \begin{cases} R_{||}\left(1 + \dfrac{\beta^2}{\gamma^2} - \dfrac{\alpha^2}{\alpha^2 + \beta^2}\right) \\ \quad + R_{\perp} \dfrac{\alpha^2}{\alpha^2 + \beta^2} & \text{TE mode} \\ R_{||}\left(1 + \dfrac{\alpha^2}{\gamma^2} - \dfrac{\beta^2}{\alpha^2 + \beta^2}\right) \\ \quad + R_{\perp} \dfrac{\beta^2}{\alpha^2 + \beta^2} & \text{TM mode} \end{cases} \tag{5}$$

where $R_{\|}$ and $R_{\perp}$ are the Fresnel reflectivities.

The gain ripple ΔG of the amplifier is given by [4]

$$\Delta G(\text{dB}) = 20 \log_{10} \left| \frac{1 + A}{1 - A} \right| \tag{6}$$

where A is given by

$$A = \sum_{i, j = 0, 1} \sqrt{K_{0i} K_{j0} G_i G_j} \exp\left(j\phi_{ij}\right). \tag{7}$$

G_i and G_j are the modal single-pass gains, and ϕ_{ij} is the difference of the single-pass phase shifts of modes i and j. To consider the worst case, we take $\phi_{ij} = 0$ in our calculations. The results obtained from this model are shown in the following.

Results

The gain ripple is used to assess the quality of the antireflection (AR)-coated facets of an amplifier; and the coating tolerances for which the gain ripple is lower than a given level can be taken as a measure for the applicability of the AR-coating technique investigated. It should be added that the bandwidth of the AR coating is increasing with the tolerances, so in order to utilize the full transmission bandwidth, large coating tolerances are also desirable. Both the gain ripple and the coating tolerances in the presence of higher order modes can be found from (6) and (7). For the angled-facet ridge waveguide amplifier under consideration, we use beam widths W_x and W_y of 0.6 and 1.3 μm as determined from measurements of the far-field patterns of actual devices [7]. The operating wavelength is 1.55 μm and the effective index is 3.28. We assume a single-pass gain for the fundamental mode of 25 dB, and a 10 dB lower gain for the first-order mode. This assumption is considered conservative since measurements of the far-field patterns did not indicate the presence of higher order modes.

Contour plots for a 1 dB gain ripple are shown in Fig. 2 in the thickness versus refractive index space of a single-layer AR coating applied to a 7° angled-facet amplifier. Results for both polarizations are shown with and without the presence of the first-order mode. A 1 dB ripple at 25 dB gain corresponds to a residual reflectivity of 10^{-4} for the single-mode case and is considered acceptable for practical applications. The overlap of the contour plots for TE and TM modes shows that for a polarization independent low ripple, the tolerances for the thickness and the refractive index of the coating layer are 400 Å and 0.2 in the case of fundamental mode operation. In the presence of the first-order mode, the tolerances are reduced by a factor of three, so even a weak higher order mode will influence the coating tolerances significantly.

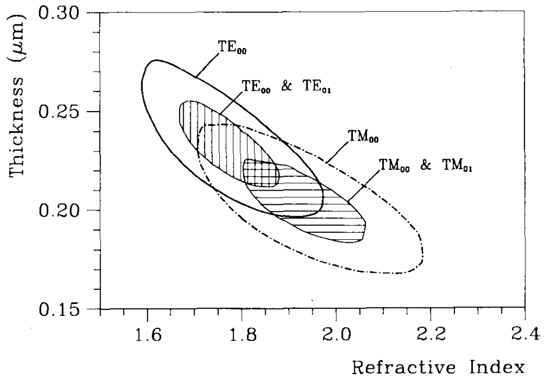

Fig. 2. Contour plots for 1 dB gain ripple in the refractive index versus coating thickness space of a single-layer AR coating. The facet angle is $\theta_0 = 7°$, and results without and with the first-order mode are shown. $G_0 = 25$ dB and $G_1 = 15$ dB.

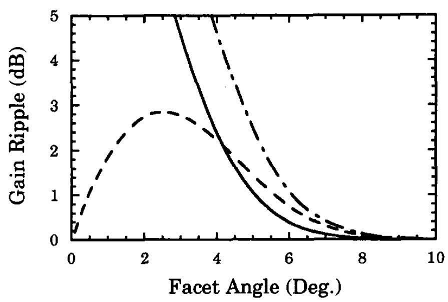

Fig. 3. Gain ripple versus facet angle for operation in the TE_{00} mode (——), the TE_{01} mode (-----), and both the TE_{00}) and TE_{01} modes (-·-·-·-). Modal gains are as in Fig. 2.

In order to get low gain ripple irrespective of the polarization, the thickness and the refractive index of the coating should be 0.22 μm and 1.84 according to Fig. 2. For this coating, the calculated gain ripples due to the fundamental mode, the first-order mode, and both modes are seen in Fig. 3 versus the facet angle θ_0 of the amplifier. Again, gains of the fundamental and the first-order modes are assumed to be 25 and 15 dB. The gain ripple is mainly due to the first-order mode for $\theta_0 > 4°$ because of high coupling coefficients K_{11} and K_{01} [see (3)] related to the first-order mode. However, the gain ripple is reduced to less than 0.2 dB for facet angles beyond 8°.

The gain of the first-order mode can vary significantly

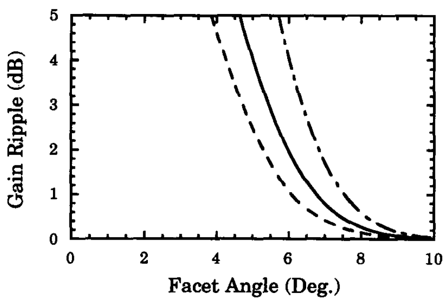

Fig. 4. Gain ripple due to both TE_{00} and TE_{01} modes versus the facet angle. G_1 = 15 dB (- - - - -), 20 dB (——), and 25 dB (-·-·-·-). G_0 = 25 dB.

depending on the waveguide structure [9]. To study the influence of the first-order mode, Fig. 4 gives the total gain ripple as a function of facet angle for gains of the first-order mode of 15, 20, and 25 dB. The gain of the fundamental mode is maintained at 25 dB. As seen, even for equal gains of the two modes, the angled facet can suppress the ripple to less than 0.2 dB for facet angles of 10°. It should be noted that the 10° facet angle will distort the far-field pattern slightly, but the resulting excess coupling losses to optimized tapered-lens-ended fibers will be lower than 0.5 dB [8].

Conclusion

Coating tolerances for a 1 dB gain ripple at 25 dB gain have been calculated for a 7° angled-facet amplifier with a single-layer AR coating. Even in the presence of a first-order mode with a 10 dB lower gain compared to the fundamental mode, a polarization independent gain ripple of less than 1 dB is possible, but the tolerances for the coating are tight. However, the ripple will decrease with the facet angle, and for facet angles of 10° the gain ripple is lower than 0.2 dB even if the gain of the first-order mode is comparable to that of the fundamental mode.

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